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A WIND TUNNEL FACILITY TO EXAMINE FLOW FIELDS AND COMPUTE PROFI--ETC(U)

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WEAPONS SYSTEMS RESEARCH LABORATORY

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TECHNICAL REPORT

WSRL-0092-TR

A WIND TUNNEL FACILITY TO EXAMINE FLOW FIELDS
AND COMPUTE PROFILE DRAG

G.H.S. PIKE

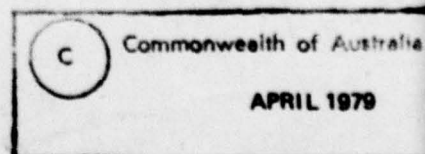
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SUMMARY

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1. INTRODUCTION

For several years, the Weapons Systems Research Laboratory (WSRL) has been concerned with the external carriage and separation of stores from aircraft. As part of this general field of research, it is frequently necessary to carry out wind tunnel testing to provide data on the flow fields close to an aircraft and so determine the conditions a store is likely to encounter in this region. In addition, there is always a need to reduce the installed drag of external stores because of their considerable effect on aircraft performance. This, in turn, implies a need for an accurate means of measuring the installed drag to determine the effects of any modifications to the store or aircraft.

This report describes a facility which has been developed at WSRL to carry out these two tasks. The S-1 wind tunnel and associated data processing equipment were employed together with an IBM 370/3033 computing system for off-line data reduction. The facility consists of a yawmeter probe mounted on a computer-controlled traverse gear system in the working section of the wind tunnel. Under the control of a PDP-15 computer, the probe is moved through a set of points in a rectangular box shaped grid. The data recorded at each grid point are processed through the data acquisition system of the S-1 complex and recorded on magnetic tape which then undergoes the final phase of data reduction on the IBM 370/3033 machine off-line. This last step enables CALCOMP plots of desired flow field parameters to be provided. Furthermore, if the appropriate traverse grid has been chosen, the momentum defect in the wake behind a model can be computed and used to obtain the profile drag.

The individual components of the facility are described in further detail in Section 2 of this report. The off-line data reduction program is discussed in Section 3. Section 4 presents some applications of this facility together with some experimental comparisons aimed at validating the drag calculations.

2. FACILITY DESCRIPTION

2.1 The wind tunnel

The facility discussed here was designed for use with the S-1 wind tunnel in the Aeroballistics Division of WSRL. It is a continuous flow tunnel, capable of subsonic operation up to Mach 1 and from Mach numbers of 1.4 to 2.8 when used supersonically. The standard subsonic working section is approximately 0.4 m x 0.4 m in cross-section.

2.2 The probe

Exploration of the flow field is performed using an hemispherical headed yawmeter probe designed to measure Mach number, flow angles and dynamic pressure. Geometrical details of the probe are given in figure 1, and figure 2 shows it in position close to a model in the wind tunnel. Pressure tappings in the probe are connected to two differential and two absolute pressure transducers outside the working section via flexible tubing. The differential transducers are connected across holes 1 to 3 and 2 to 4 (see figure 1) and so give outputs dependent on the flow angles (downwash and sidewash) experienced by the probe. The absolute transducers measure the pressures at hole 5 and the manifold.

The electrical outputs of the transducers are fed via appropriate interfaces to the data acquisition system attached to the tunnel and controlled by the PDP-15 computer. Further details on the design, calibration and setting-up of the probe are given in reference 1, while the software and hardware concerned with the data acquisition system are discussed in detail in references 2 and 3.

2.3 The traverse gear

The probe is attached to a traverse gear which is capable of motion in 3 orthogonal directions under either manual or computer control by the PDP-15 computer. Full details of both the hardware and the computer commands needed to invoke the grid traverse program are also given in references 2 and 3. For the task discussed here, computer control with the standard grid traverse program was used exclusively.

The computer is programmed to move the probe through a rectangular box defined in terms of "box axes" (X_B, Y_B, Z_B) by starting coordinates (X_S, Y_S, Z_S) , finishing coordinates (X_F, Y_F, Z_F) and increments $(\Delta X_B, \Delta Y_B, \Delta Z_B)$. This together with the required pitch angle (θ_B) of the box relative to wind tunnel axes (X_T, Y_T, Z_T) , defines a three dimensional grid of points with flow field data being measured at each point. The axis systems and the pitch angle θ_B are explained in figure 3. Box axes and tunnel axes are assumed to be based on the same origin which, when dealing with aircraft models, is frequently taken to be at the centre of gravity of the aircraft.

In practice, most investigations employ only a two dimensional grid of points. For example, a wake traverse to compute the profile drag of a model requires a traverse grid in a plane perpendicular to the freestream (or X_T) direction. This is obtained by setting $X_S = X_F$, $\Delta X_B = 0$ and $\theta_B = 0$ when executing the grid traverse program on the PDP-15. The majority of flow field investigations have been carried out in a plane perpendicular to the Y_T axis and specified in an analogous fashion.

Experience has shown that between 3 and 5 s settling time must be allowed after the probe is moved to a new position to enable the signals from the pressure transducers to reach a steady value. The grid traverse program enables this delay to be selected by the experimenter and it is then automatically controlled by the computer.

2.4 The PDP-15 computer

As can be inferred from the discussion so far, the PDP-15 computer has a major role to play in both controlling the execution of the experiment and providing on-line data acquisition. During the running of the experiment, real-time data processing is confined to analysing the outputs from the pressure transducers, converting these to pressures using calibration data held in the computer and storing the results on 7-track magnetic tape (the primary tape). Later, the PDP-15 "probe processor" program is used off-line to combine this information with probe calibration data established separately (ref.1) and to store the computed flow field parameters at each grid point on a second 7-track tape (the secondary tape). This tape is then submitted for processing on the IBM 370/3033 with program IG2.61.1/D. Subsequent stages of processing are discussed in Section 3 while the general flow of data manipulation is represented schematically in figure 4.

3. PROGRAM IG2.61.1/D

3.1 Program organisation and availability

The version of the data reduction program IG2.61.1/D (version 1.4) described here consists of four subprograms which are executed by a short main program at the discretion of the user. It is currently coded in IBM FORTRAN IV for use on the 370/3033 computer operating in the batch or non-interactive mode. Each subprogram is logically independent of any other and can be executed separately. As they are processed through the subprograms, the data originally generated in the wind tunnel are stored on intermediate disc datasets for use by other subprograms.

These datasets are formatted to enable any spurious data to be modified manually by using the IBM Time Sharing Option (TSO) EDIT facility from a remote terminal(ref.4).

It is hoped that most error conditions have been anticipated and indicated by messages in the printed output generated by the program. A detailed discussion of the data required to be supplied by the user will not be given here as the listings of both the program IG2.61.1/D and the Job Control Language (JCL) statements needed to execute it on the IBM machine are available from the Aerodynamic Research Group in WSRL. The program listing contains numerous "comment" statements explaining the function of each data item which must be provided. This listing also includes comments detailing the contents of each word in each record on the intermediate disc datasets. The program can also be supplied in the form of 80 column punched card decks or copies on magnetic tape.

For the convenience of the user, Table 1 has been prepared. This relates the symbols used in this report to their equivalent variable names in the program. It is expected that this list should simplify either understanding the detailed workings of the program or modifying it.

In addition to the main calling program (labelled MAIN), IG2.61.1/D consists of the four subprograms (COPY, DATRED, PLOTG and DRAG) mentioned above and 11 other subroutines. The function of each subprogram will be discussed in the following sections.

3.2 Subprogram COPY

Each secondary tape produced by the probe processor (labelled logical unit 9) is first copied to a disc dataset (labelled logical unit 10) and this is the task of subprogram COPY. Data are read sequentially, one record at a time off the tape. Each record is checked to see if it is within the range of records specified by the user to be accepted and, if so, copied to unit 10. Each record contains data measured at one grid point. No data reduction is done at this stage but experience has shown the following two features to be desirable and they have been incorporated in COPY.

- (a) Particularly when measuring drag by the wake traverse technique, it is often realised after a grid has been executed and the data recorded that it was not large enough to cover the required region of the flow field. Provision is therefore made in COPY to merge the results from an additional grid obtained from a later tunnel run to data already on unit 10. Provided the combined grid contains all the points needed to define a grid of regularly spaced points, subsequent processing will treat the data now on unit 10 as if they were all recorded during the same run of the grid traverse program. The order in which the data records are copied to unit 10 is not important.
- (b) Human error can cause a data word in a record to be recorded incorrectly as the experiment is in progress. For example, the experimenter manually sets a run number and a nominal working section Mach number to be written on each record on the primary and secondary tapes. These particular parameters do not affect either the running of the experiment or any other data recorded on tape. However, if they are recorded incorrectly, subsequent processing might be affected. COPY possesses the capability to change any data word in each record within a specified range of records to any given value. This can be done for any or every record read off the secondary tape and causes it to be corrected before it is copied to unit 10. "Bulk editing" in this fashion has saved a considerable number of repeated wind tunnel runs.

3.3 Subprogram DATRED

Limitations of the wind tunnel data acquisition system mean that the experimenter cannot define the spatial order in which the grid is traversed and the subsequent sequence of records on both the primary and secondary tapes and the dataset unit 10.

This is inconvenient as later processing assumes that data are available in some known order, e.g., records recorded at increasing X_B , the Y_B and finally Z_B grid coordinates. DATRED has the ability to re-arrange data read off unit 10 and store them on another disc dataset (logical unit 11) in any specified order. To do this, a parameter K_D must be specified by the user. K_D takes an integer value between 1 and 6 corresponding to the six different ways of arranging the grid coordinates X_B, Y_B, Z_B . Table 2 indicates the value of K_D appropriate to the various combinations. That coordinate allowed to vary most rapidly from record to record on unit 11 is in column 1 of the table while the coordinate which changes least is in column 3. To obtain the drag on a body using the wake traverse technique, K_D must take the value of 1 or 2. Most flow field studies have been performed parallel to the $X_B Z_B$ plane with K_D equal to 3 or 4.

The sorting process depends on the user repeating the information which defined the original traverse box, namely the starting coordinates (X_S, Y_S, Z_S), finishing coordinates (X_F, Y_F, Z_F), increments ($\Delta X_B, \Delta Y_B, \Delta Z_B$) and the pitch angle of the box (θ_B) which together define a nominal set of grid points. Depending on the sequence indicated by K_D , an attempt is made to match the coordinates of each point in the nominal grid with those of a point on unit 10. A positional tolerance (E) is applied when matching the points to allow for accumulated truncation errors during the various stages of processing. If a match is not made, an error message is printed advising the user to either:

- (a) repeat the whole tunnel run and all subsequent stages of data processing or,
- (b) repeat the tunnel test for the missing point and merge it to the existing data on unit 10 using COPY. Execute DATRED again, or
- (c) insert a manually computed record into the data on unit 10 or 11 using the EDIT facility of IBM TSO.

A complete set of data at all nominal grid points must be present on unit 11 for subsequent stages of processing to be successful.

During this step, the measured flow angles (α_p, β_p) are used to compute flow angles (α_T, β_T) in tunnel axes (X_T, Y_T, Z_T in figure 3).

The following expressions are used:

$$\alpha_T = \alpha_p - \theta_p, \quad (1)$$

$$\beta_T = \tan^{-1} \left(\frac{\tan(\beta_p)}{\cos(\theta_p) + \tan(\alpha_p) \sin(\theta_p)} \right). \quad (2)$$

This conversion enables the probe to be pitched by an angle θ_p (see figure 3) to reach otherwise inaccessible regions near a model, yet still provide flow angle data in a standard set of axes. Figure 2 depicts the probe pitched towards the floor of the working section such that $\theta_p = -10^\circ$.

3.4 Subprogram PLOTG

Flow field and wake traverse surveys invariably generate large quantities of data which cannot readily be absorbed if presented solely as a listing of data recorded at each grid point. With this in mind, PLOTG was written to take information off unit 11 and plot it on a CALCOMP plotter. A typical plot is given in figure 5. In this example, the total pressure measured at the probe divided by the freestream total pressure (labelled PTOT/PTOTO on the plot) is plotted against the dimensionless box coordinate Z_B/\bar{c}

(labelled ZB/CBAR). \bar{c} is a non-dimensionalizing length. Each separate graph in this particular plot pictures the results at a constant value of Y_B/\bar{c} whose value is given at the top of each graph (labelled YB/CBAR).

X_B/\bar{c} is constant for the whole plot and is given in the top left corner (labelled XB/CBAR). The horizontal axis scale applies to the left most graph only and each subsequent graph is shifted to the right by a fixed amount designated by the user who also supplies the title printed across the top of the plot.

Six parameters can be plotted on the vertical axis. They are:

- (1) Downwash, (α_T)
- (2) Sidewash, (β_T)
- (3) Local Mach number, (M_p)
- (4) Local dynamic pressure/Freestream dynamic pressure, (q_p/q_o)
- (5) Local total pressure/Freestream total pressure, (P_p/P_o)
- (6) Local static pressure/Freestream static pressure, (p_p/p_o)

The vertical axis represents one of the following three non-dimensional positional coordinates, (X_B/\bar{c} , Y_B/\bar{c} , Z_B/\bar{c}). The relevant one is automatically selected by PLOTG depending on the value of K_D chosen when DATRED was executed and it corresponds to the grid coordinate given in column 1 of Table 2.

A plot of this nature can only represent the results of a two-dimensional traverse, even though the original wind tunnel traverse might have been in three dimensions. Consequently, PLOTG assumes that the data on unit 11 is divided into blocks, each block consisting of a set of data taken at a constant value of that grid coordinate which varies least rapidly on unit 11 (i.e., the coordinate in column 3 of Table 2). The user must indicate the number of the block on unit 11 to be plotted. One block is plotted on each call to PLOTG from the main program.

Each symbol on the graphs represents one grid point and provision is made in PLOTG to correct these points either by a straight line or a smooth curve generated by the cubic spline curve fitting technique discussed in Appendix I.

3.5 Subprogram DRAG

If a two-dimensional rectangular grid perpendicular to the freestream direction downstream of a model is explored, the resulting distribution of total pressure and Mach number can be used to estimate the profile drag experienced by the model. This is expressed as a drag coefficient (C_D) defined in equation II.3 of Appendix II where the analysis is presented in some detail. The calculations are performed by subprogram DRAG.

As with PLOTG, the data on unit 11 are assumed to be divided into blocks, each block containing data from one wake traverse at one value of X_B . As mentioned in Section 3.3, this means that K_D must be specified as either 1 or 2 when the data from unit 10 is passed through DATRED. One block of data is processed on each entry to DRAG and the user must supply the number of the block on unit 11 which is to be analysed.

4. EXAMPLES OF DRAG CALCULATIONS

4.1 General comments

To date, the calculation of drag using IG2.61.1/D has been limited to finding the installed drag on various combinations of stores carried on racks and/or pylons mounted externally beneath the wing or fuselage of an aircraft. To do this, a wake traverse of sufficient extent to include the entire effects on the wake of the model attributable to the store is performed. The installed drag of the store alone is obtained by repeating the same wake traverse with the store removed and differencing the two results.

The required size of the traverse would be difficult to ascertain were it not for the plotting facility available in subprogram PLOTG. A plot of total pressure (as in figure 5) quickly establishes whether or not a grid is large enough. It also provides an indication of the spacing between grid points required to resolve variations in the wake parameters. A typical wake traverse grid to measure the installed drag on a store mounted on a cylindrical fuel tank beneath the wing of a 1/24 scale model with a wingspan of 0.343 m would be (in inches - as required by the grid traverse program on the PDP-15 computer)

Starting coordinates: $X_S = -6.0$, $Y_S = -0.9$, $Z_S = -1.2$

Finishing coordinates: $X_F = -6.0$, $Y_F = +1.0$, $Z_F = +1.2$

Increments: $\Delta X_B = 0.0$, $\Delta Y_B = +0.1$, $\Delta Z_B = +0.1$

Box incidence: $\theta_B = 0.0$ degrees.

The origin of these coordinates is the rear of the centre line of the fuel tank.

4.2 Two experimental comparisons

Two cases are given which compare the technique discussed in this report to compute the drag of external stores with other experimental and published values.

Figure 6 shows the experimental results from tests with a 1/50 scale model of a variable geometry aircraft carrying six stores on one rack/pylon assembly under each wing. Results are given for the drag increment (ΔC_D) due to:

- (i) the addition of the stores alone, and
- (ii) the effects of carrying the bare rack/pylon.

These are compared with data derived from a combination of flight and wind tunnel testing using a geometrically similar store and published in the aircraft's flight manual. Two cases of nominal wing sweep (40° and 54°) were considered at Mach numbers between 0.7 and 0.9. The differences between the two sets of results are within the bounds normally accepted for drag measurements, especially after the large differences in scale and Reynolds number between the sources of data are considered.

The second example is depicted in figure 7. In this case, the comparison is with existing data obtained previously at WSRL from a wind tunnel test on a 1/50 scale model of an aircraft carrying four stores on an underwing carrier on each wing. A Mach number of 0.8 was used. For the original tests, the model was mounted on a strain gauge equipped sting type force balance and the drag recorded directly at several aircraft angles of attack between -5° and $+10^{\circ}$. The wake traverse tests were performed on the same model at the same Reynolds number using a simpler uninstrumented sting support. The deflection of the sting under aerodynamic loads was taken into account when obtaining the actual angle of attack of the model.

There are a number of possible explanations for any differences between the results from the two techniques but the most significant ones appear to be that the accuracy of the drag component of the force measurement balance is approximately ± 0.0010 in ΔC_D , close to the observed differences. In addition, at the time the force measurement tests were made, the Mach number distribution in the wind tunnel's working section possessed several irregularities, especially near the model. This has been since corrected by a detailed re-design of the model support system and tunnel walls(ref.5).

5. CONCLUSIONS

The wind tunnel facility described in this report has reached a high level of operational efficiency. It has been used for a number of projects over a period of nearly two years and, wherever possible, has been verified by comparison with data derived from other sources.

NOTATION

A	reference area for C_D (equation II.3)
C, K	constants of integration (equations I.3, I.4)
C_D	drag coefficient (equation II.3)
ΔC_D	an increment in C_D due to the addition of stores
D	drag (equation II.2 and figure 8)
F_1, F_2, F_3	equations II.7, II.8 and II.9
F	a function
G_1, G_2, G_3	equation II.5
I	an integral (equation I.6)
I_k	an integral over a sub interval (equation I.8)
K_D	selection parameter (see Table 1)
M	the second derivative of an interpolation function (equation I.1) or the number of integration points in the y direction, or the Mach number
N	the number of points in a numerical integration in the x direction (equation I.7)
P	total pressure
S	a surface integral
X_B, Y_B, Z_B	box axes (see figure 3)
X_F, Y_F, Z_F	finishing coordinates in defining a traverse box (inches)
X_P, Y_P, Z_P	probe axes (see figure 3)
X_S, Y_S, Z_S	starting coordinates in defining a traverse box (inches)
X_T, Y_T, Z_T	tunnel axes (see figure 3)
$\Delta X_B, \Delta Y_B, \Delta Z_B$	increments along box axes
\bar{c}	the reference length for coordinates (inches)
k	a counting index
l	the distance between successive grid points

p	static pressure
q	dynamic pressure
u	velocity in the X_T direction
u_p, v_p, w_p	velocity components in probe axes (see figure 3)
u_T, v_T, w_T	velocity components in tunnel axes (see figure 3)
x, y	cartesian coordinates (usually with a subscript)
α_p	downwash in probe axes = $\tan^{-1} \left(\frac{w_p}{u_p} \right)$
α_T	downwash in tunnel axes = $\tan^{-1} \left(\frac{w_t}{u_t} \right)$
β_p	sidewash in probe axes = $\tan^{-1} \left(\frac{v_p}{u_p} \right)$
β_T	sidewash in tunnel axes = $\tan^{-1} \left(\frac{v_T}{u_T} \right)$
γ	ratio of specific heats = 1.4
e	the spatial tolerance of a grid point
θ_B	the pitch of the traverse box (see figure 3)
θ_p	the pitch of the probe (see figure 3)
ρ	air density
subscripts (where not stated explicitly elsewhere)	
$0, \infty$	pertaining to freestream conditions
1	a quantity at station 1 (figure 8)
2	a quantity at station 2 (figure 8)
∞	a quantity at station ∞ (figure 8)
B	pertaining to the traverse box
T	pertaining to the tunnel
p	pertaining to quantities measured by the probe
k	a counting index

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TABLE 1. SYMBOLS WITH EQUIVALENT VARIABLE NAMES

Symbol in text	FORTTRAN variable name
A	REFA
C	CONSTC
C_D	CD
K	CONSTK
K_D	KODORD
D	PDRAG
F_1, F_2, F_3	F1, F2, F3
G_1, G_2, G_3	RRI, UUI, UJUI
I	SPLINT
M	MN, MACHI
M_p, M_2	RMACH, MACH
P_o, P_∞	PTOTO
P_p, P_2	PTOTP
X_B, Y_B, Z_B	TRX, TRY, TRZ
X_F, Y_F, Z_F	XEND, YEND, ZEND
X_S, Y_S, Z_S	XSTART, YSTART, ZSTART
$\Delta X_B, \Delta Y_B, \Delta Z_B$	XINC, YINC, ZINC
\bar{c}	CBAR
P_o, P_∞	STATO
P_p, P_2	STATP
q_o, q_∞	QO
q_p, q_2	Q
a_p	ALFA, DOWN
a_T	ALFW
β_p	BETA, SIDE
β_T	BETAW
γ	GAMMA
E	ERROR
θ_B	THETAB
θ_p	THETAP

TABLE 2. THE VALUE OF SEQUENCING PARAMETER K_D

K_D	MOST RAPIDLY VARYING COORDINATE COLUMN 1	COLUMN 2	LEAST RAPIDLY VARYING COORDINATE COLUMN 3
1	Z_B	Y_B	X_B
2	Y_B	Z_B	X_B
3	X_B	Z_B	Y_B
4	Z_B	X_B	Y_B
5	Y_B	X_B	Z_B
6	X_B	Y_B	Z_B

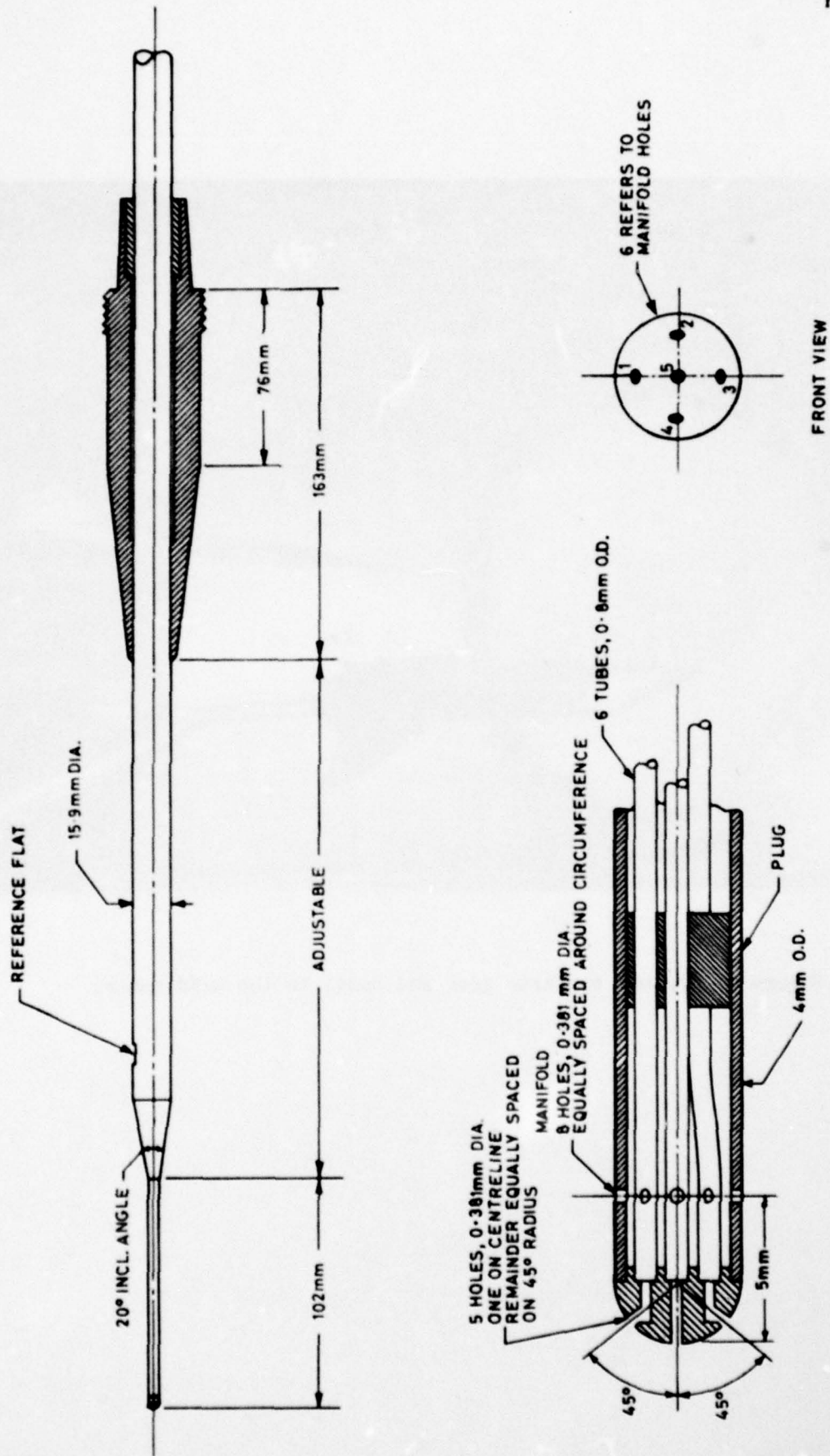


Figure 1. General arrangement of yawmeter probe and mounting

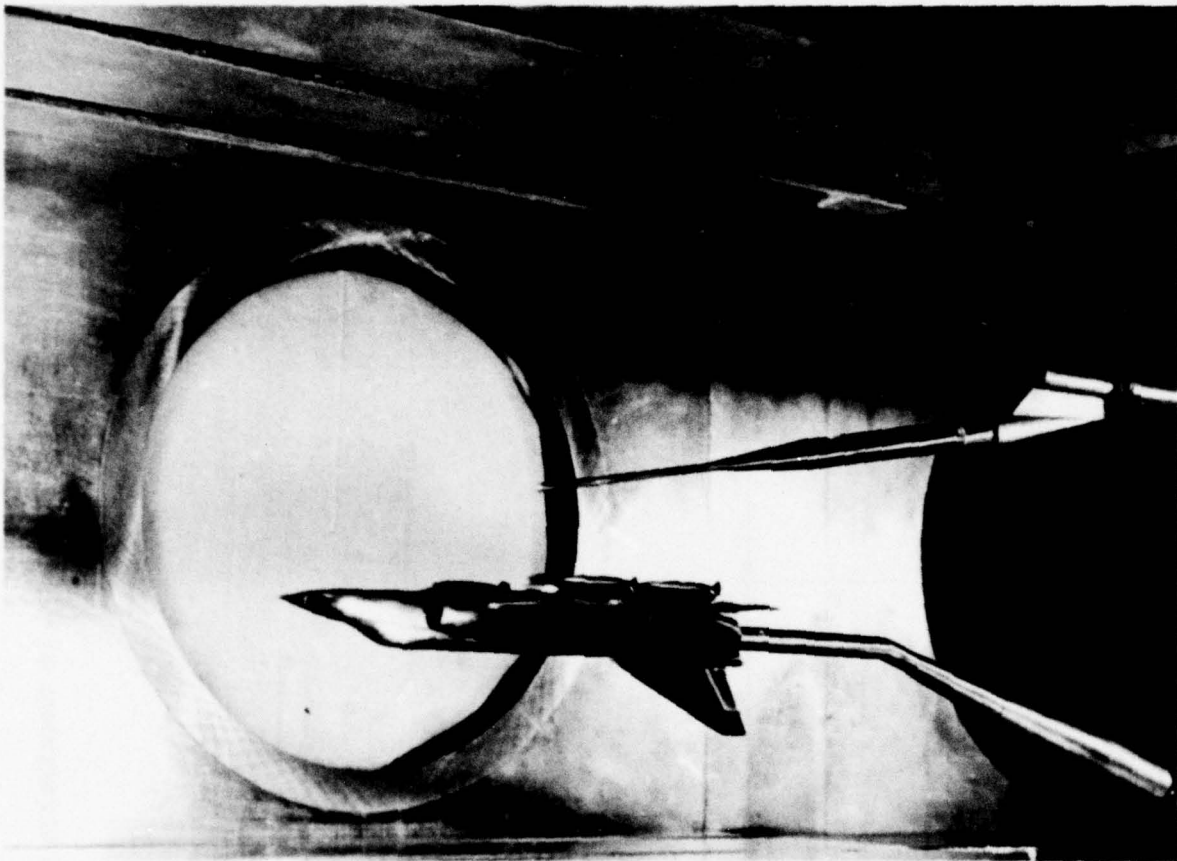


Figure 2. Probe, traverse gear and model in the wind tunnel

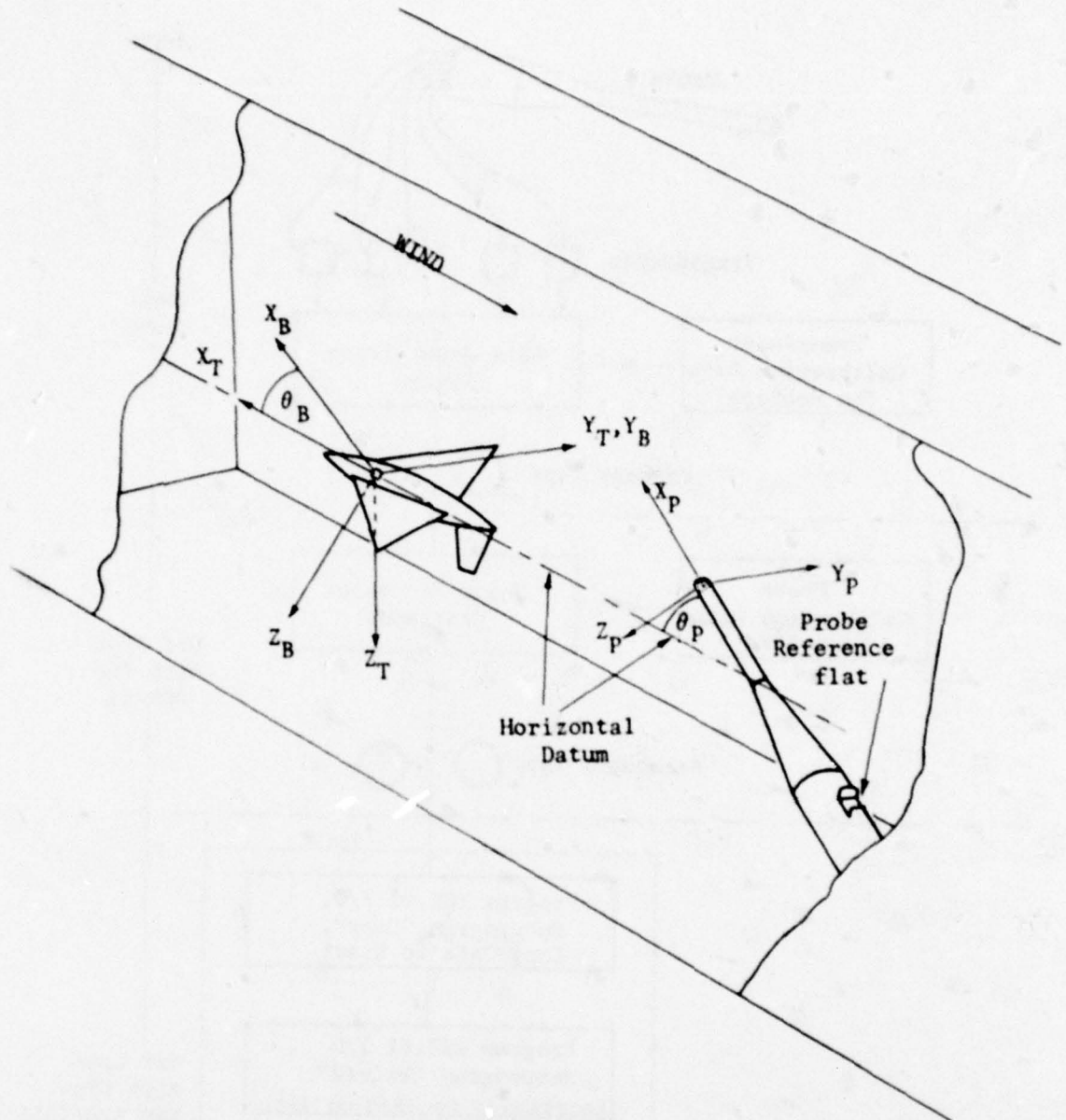


Figure 3. Definition of axes and pitch angles

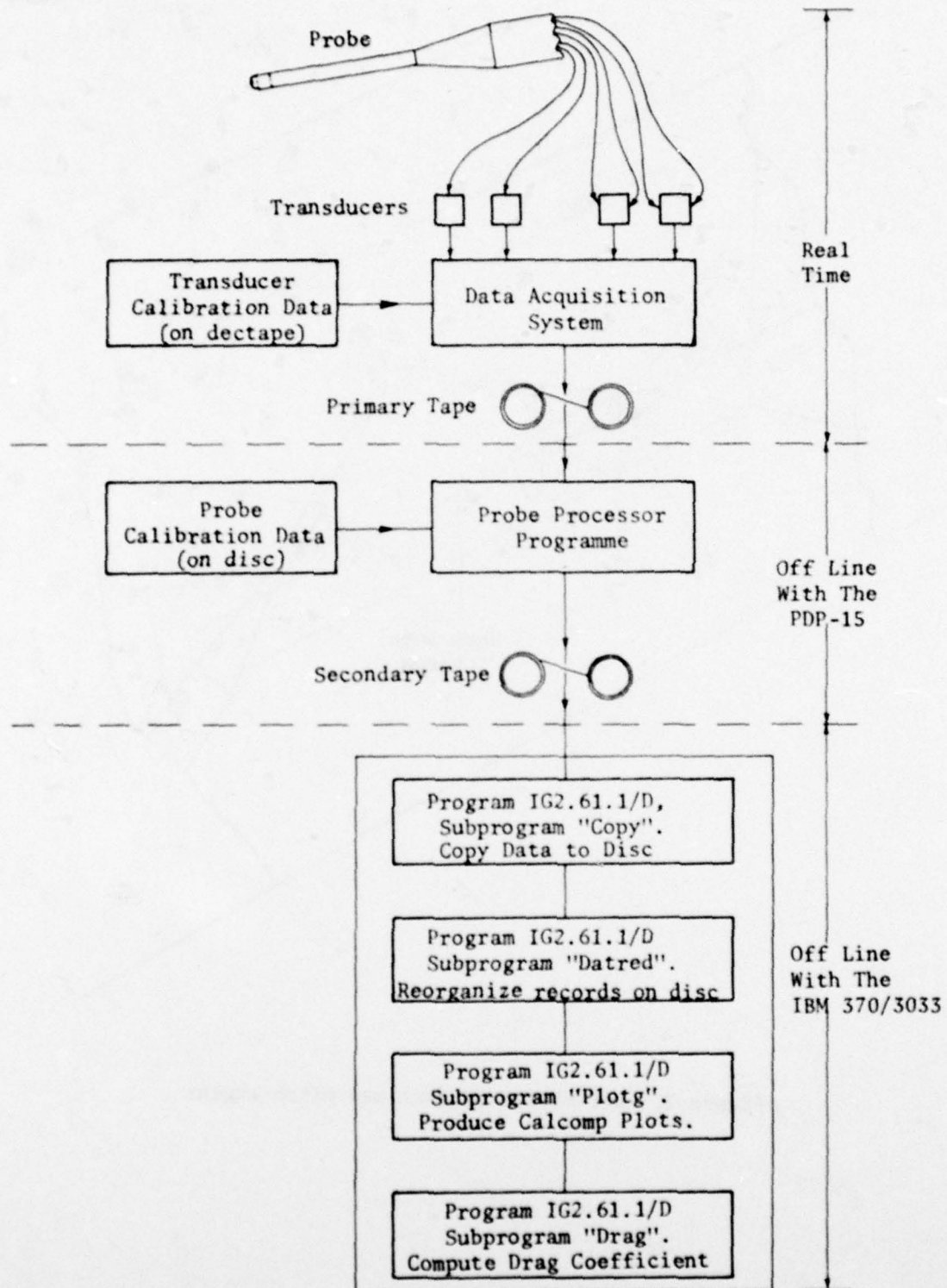


Figure 4. Flow of data through the facility

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XB/CBAR=-3.000

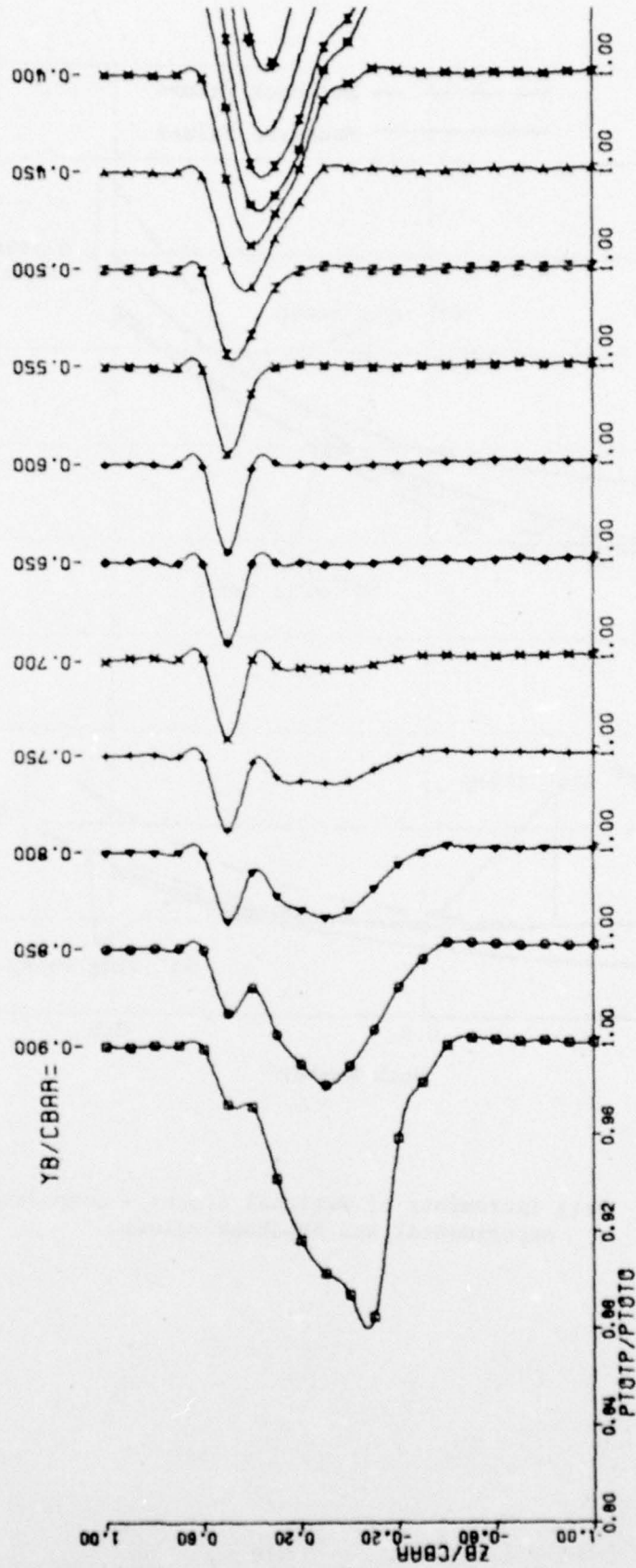


Figure 5. Typical CALCOMP plot from PLOTG

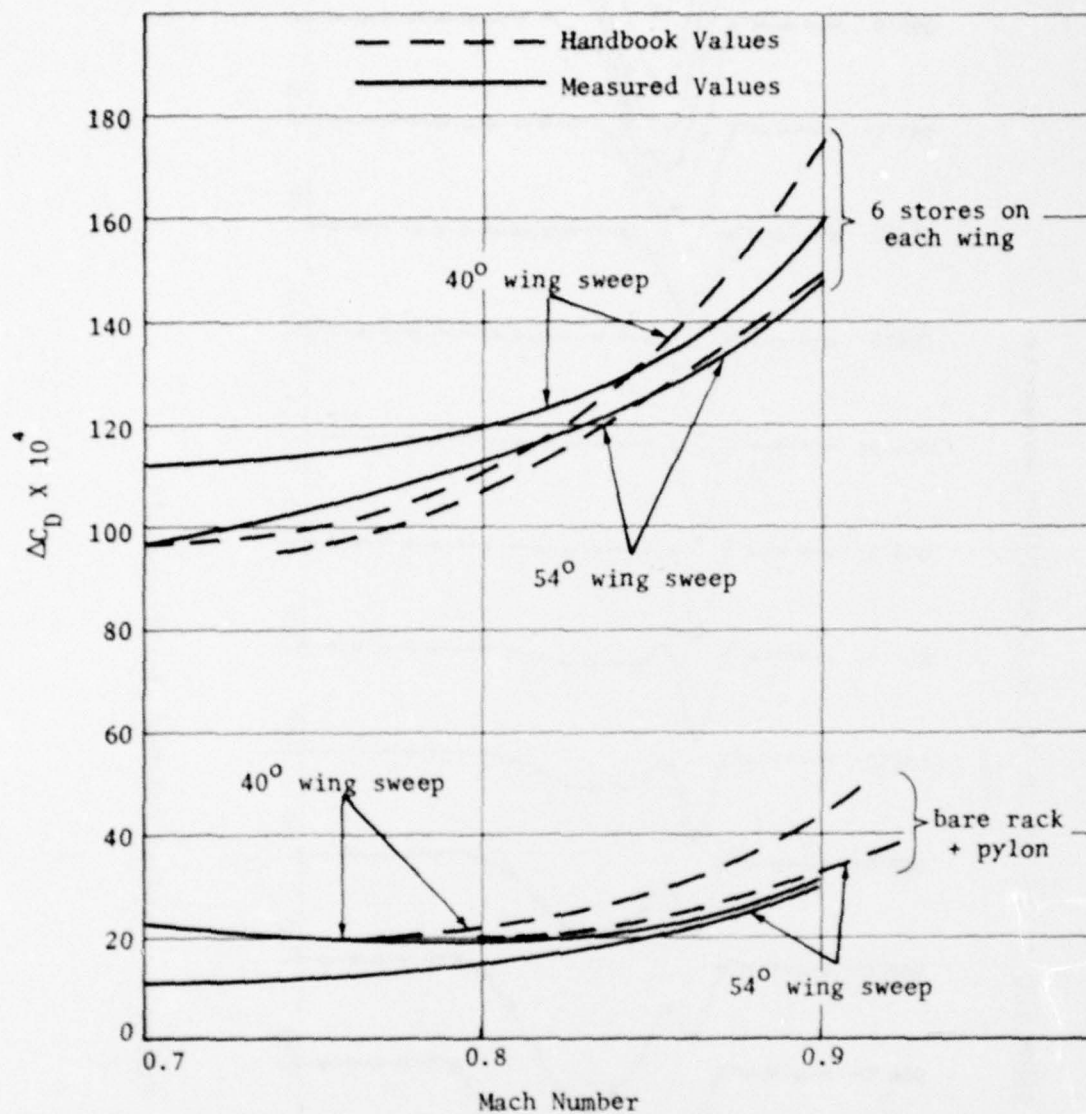


Figure 6. Drag increments of external stores - comparison of experimental and handbook values

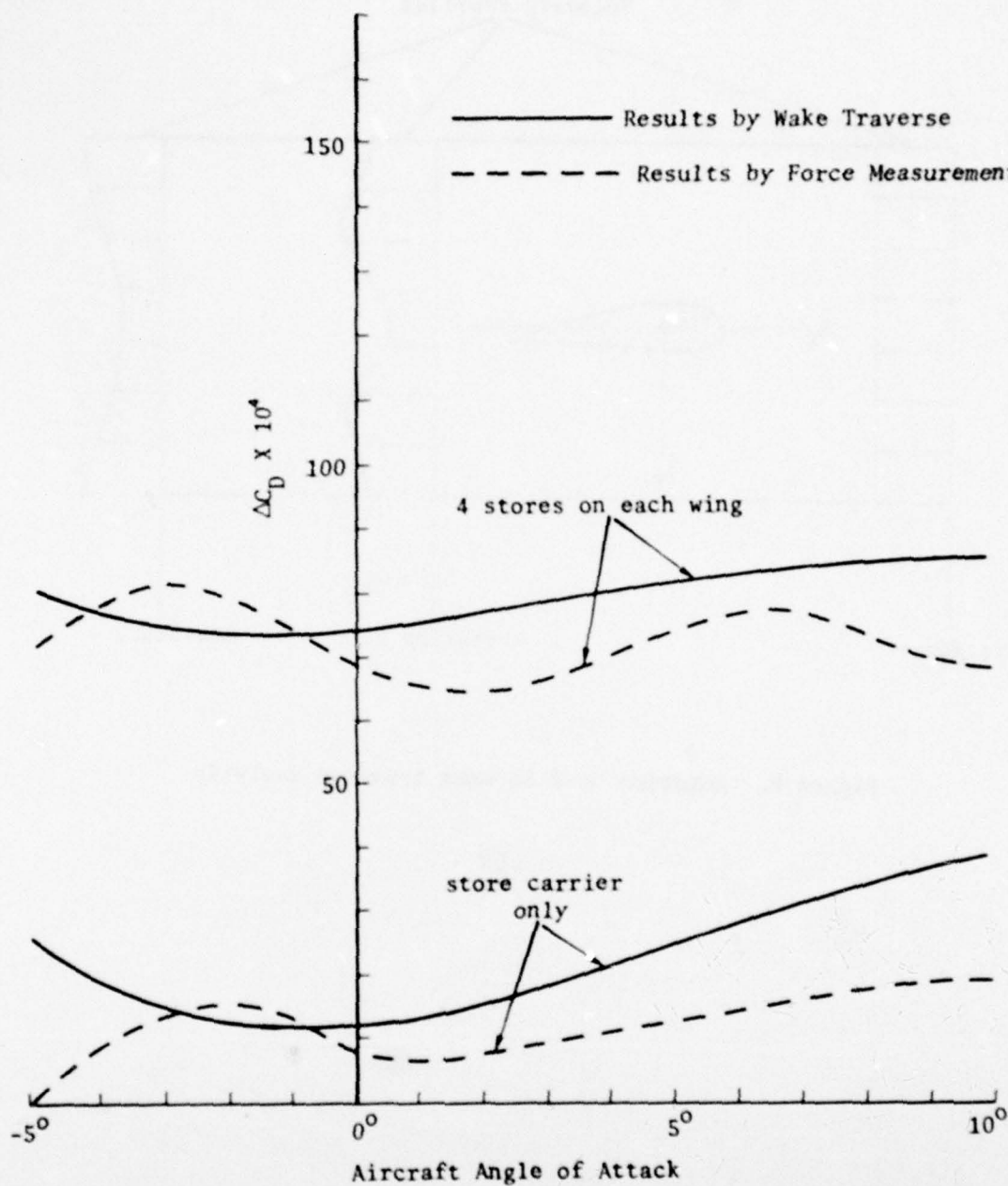


Figure 7. Drag increments of external stores - comparison of wake traverse and force measurement techniques

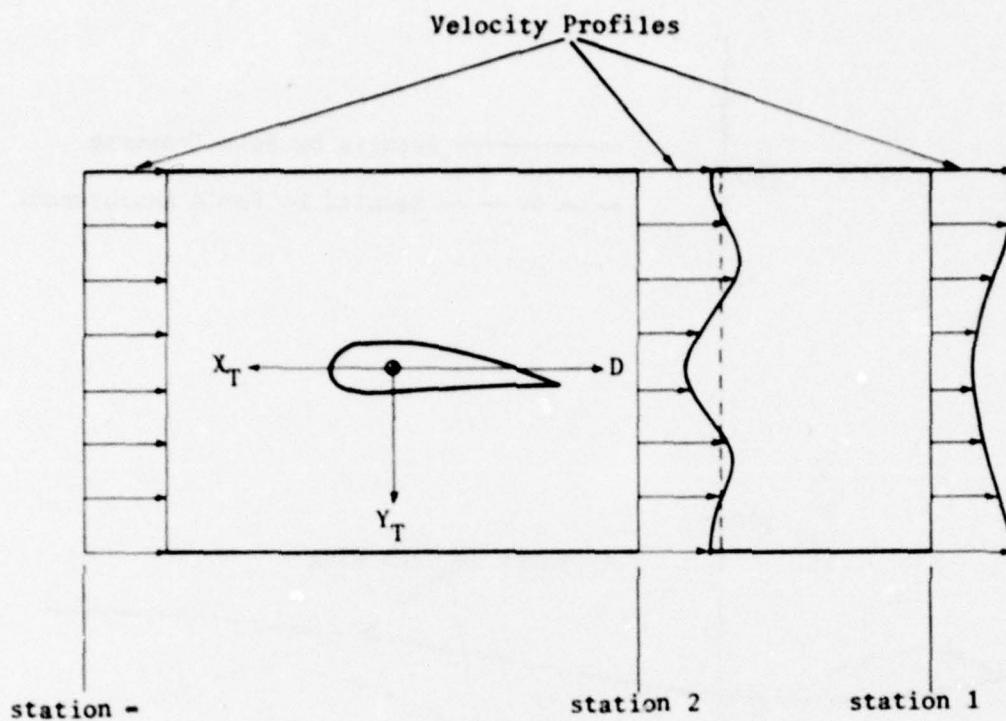


Figure 8. Notation used in wake traverse analysis

APPENDIX I

THE CUBIC SPLINE CURVE FIT AND INTEGRATION

I.1 General

The computer program IG2.61.1/D described in the body of this report requires an algorithm which will provide an analytical expression for an accurate curve through a given set of points. These curves are used in two roles:

- (1) to provide interpolation points between measured grid points as required by the plotting subprogram PLOTG. Because the CALOMP plotter is constrained to draw a straight line between two points, the impression of a smooth curve is generated by locating a number (typically 10 to 20) of interpolation points between each plotted grid point and joining these with straight lines, and
- (2) to form the basis for a numerical surface integration over a rectangular region as used to evaluate the drag on a body using the wake traverse technique. Equation II.2 of Appendix II gives the expression to be evaluated by this means.

Both roles were filled by a cubic spline curve fit as described and derived by Walsh et al. (ref.6). The following is an extended version of that derivation with emphasis on those specific aspects used in IG2.61.1/D.

I.2 The interpolation function

Suppose a function $(F(x))$ is prescribed by y_k at $N+1$ discrete values of x , denoted by x_k where $k=0, 1, 2 \dots N$. Let M_k denote the second derivative of the approximate interpolation function $y(x)$. Further, assume that M_k varies linearly between any two points so that

$$y''(x) = M_{k-1} \frac{x_k - x}{l_k} + M_k \frac{x - x_{k-1}}{l_k}, \quad x_{k-1} \leq x \leq x_k, \quad I.1$$

where

$$l_k = x_k - x_{k-1}.$$

Integrating I.1 twice and applying the conditions that

$$x = x_k \quad \text{at} \quad y(x_k) = y_k$$

$$\text{and} \quad x = x_{k-1} \quad \text{at} \quad y(x_{k-1}) = y_{k-1},$$

leads to

$$y(x) = \frac{M_{k-1} (x_k - x)^3}{6l_k} + \frac{M_k (x - x_{k-1})^3}{6l_k} + Cx + K, \quad I.2$$

where

$$C = \frac{(y_k - y_{k-1})}{\ell_k} - \frac{\ell_k (M_k - M_{k-1})}{6} \quad 1.3$$

and

$$K = -x_{k-1} \left(\frac{y_k}{\ell_k} - \frac{M_k \ell_k}{6} \right) + x_k \left(\frac{y_{k-1}}{\ell_k} - \frac{M_{k-1} \ell_k}{6} \right). \quad 1.4$$

Equation 1.2 is the interpolation function used in the first role mentioned above. The only terms not given explicitly by the set of points (x_k, y_k) in equations 1.2, 1.3 and 1.4 are the M_k, M_{k-1} terms. These are obtained by applying the condition of continuity of slope at each point, that is

$$y' (x_k^-) = y' (x_k^+) . \quad 1.5$$

This condition leads to a set of linear simultaneous equations which are readily solved by matrix inversion.

1.3 The surface integral

If it is assumed that a one dimensional integral of the type

$$I = \int_{x=x_0}^{x=x_N} F(x) dx \quad 1.6$$

can be represented by sums of individual integrals (I_k) over each sub-interval such that

$$I = \sum_{k=1}^{k=N} I_k = \sum_{k=1}^{k=N} \int_{x=x_{k-1}}^{x=x_k} F(x) dx , \quad 1.7$$

it is clear that the integral (equation 1.6) can be evaluated by examining the I_k terms in isolation.

$$I_k = \int_{x=x_{k-1}}^{x=x_k} F(x) dx \quad 1.8$$

can be approximated by the interpolation function derived above, (equation 1.2) such that

$$I_k \triangleq \int_{x=x_{k-1}}^{x=x_k} y(x) dx . \quad 1.9$$

Substituting equation I.2 yields

$$I_k \triangleq \frac{\ell_k^3}{24} (M_k + M_{k-1}) + \frac{c}{2} (x_k + x_{k-1}) \ell_k + K \ell_k, \quad I.10$$

which can be evaluated since all terms are known or can be derived using methods discussed in Section I.2. The approximation to the integral I (equation I.6) follows from equation I.7.

A numerical surface integration over a plane, rectangular surface defined in cartesian coordinates (x,y) and containing a grid of points disposed rectilinearly in the x and y directions merely involves the same procedure carried out in two directions.

Consider the surface integral S given by

$$S = \int_{y=y_0}^{y=y_M} \left\{ \int_{x=x_0}^{x=x_N} F(x) dx \right\} dy. \quad I.11$$

Numerical approximation of S reduces to evaluating the "inner" integral (within the brackets { }) along all the rows points at each value of x and storing the results. These form the basis for a new set of data which are then integrated by the same technique in the y direction.

APPENDIX II

DERIVATION AND EVALUATION OF THE DRAG EQUATION

The following derivation is an extension of the work of Schlichting (ref. 7, chapter 25). Lock (ref. 8) can also be consulted for a similar analysis.

Consider three planes, all of which are aligned perpendicular to the free-stream direction. These are indicated in two dimensions in figure 8 and are designated stations ∞ , 1 and 2. The first plane (station ∞) is sufficiently far upstream of the body whose drag is being measured to be regarded as having freestream conditions existing at all points on it. Station 1 is located far enough downstream of the body that the static pressure (p_1) there is essentially that of the freestream, i.e.,

$$p_1 = p_{\infty} \quad \text{II.1}$$

Typically, station 1 is so far downstream of the body that wake traversing is not feasible there. A third plane (station 2) is therefore used for the actual traverse. The static pressure at a point on station 2 (p_2) is, in general different from p_{∞} .

Momentum considerations, and the assumption that the total pressure along a streamline between stations 1 and 2 is constant (i.e., $P_2 = P_1$) leads to the following expression for the profile drag (D) on the body

$$D = \iint_{S_2} \rho_2 u_2 (u_{\infty} - u_1) dS_2 \quad \text{II.2}$$

ρ_2 and u_2 are the air density and velocity in the freestream (X) direction at station 2. u_{∞} and u_1 are the X velocity components in the freestream and at station 1 respectively. In terms of a drag coefficient (C_D)

$$C_D = \frac{D}{\frac{1}{2} \rho_{\infty} u_{\infty}^2 A} \quad \text{II.3}$$

$$= \frac{2}{A} \iint \frac{\rho_2}{\rho_{\infty}} \frac{u_2}{u_{\infty}} \left(1 - \frac{u_1}{u_{\infty}} \right) dS_2, \quad \text{II.4}$$

where A is a convenient reference area. The output from the probe processor program on the PDP-15 consists of the freestream values of total pressure and Mach number (P_{∞} and M_{∞}) with the same quantities measured at grid points at the measurement station 2. (P_2 and M_2). These terms must be used when evaluating equation II.4.

It is convenient to define

$$G_1 = \frac{\rho_2}{\rho_{\infty}}, \quad G_2 = \frac{u_2}{u_{\infty}}, \quad G_3 = \frac{u_1}{u_{\infty}} \quad \text{II.5}$$

Using several of the standard relationships of compressible gas dynamics and the assumptions that $P_2 = P_1$, $p_1 = p_{\infty}$ it follows that

$$\frac{P_1}{P_1} = \left(1 + \frac{\gamma-1}{2} M_1^2 \right)^{\frac{\gamma}{\gamma-1}} = \frac{P_2}{P_{\infty}} \quad \text{II.6}$$

Hence define

$$F_1 = \frac{2}{M_1^2} = \left[\left(\frac{P_2}{P_\infty} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{-1}, \quad \text{II.7}$$

in which γ is the ratio of specific heats ($= 1.40$). In addition, define

$$F_2 = \frac{2}{M_\infty^2}, \quad \text{II.8}$$

$$F_3 = \frac{2}{M_2^2}. \quad \text{II.9}$$

It is well established in the literature that

$$\frac{\rho}{\rho_\infty} = \left[\frac{1 + \frac{\gamma-1}{2} M_\infty^2}{1 + \frac{\gamma-1}{2} M^2} \right]^{\frac{1}{\gamma-1}} \quad \text{II.10}$$

and

$$\frac{u}{u_\infty} = \left[\frac{\frac{2}{M_\infty^2} + \gamma - 1}{\frac{2}{M^2} + \gamma - 1} \right]^{\frac{1}{2}}. \quad \text{II.11}$$

The lack of a subscript of ρ , u and M implies a quantity measured at any point in the flow field. Referring specifically to stations 1 and 2, equations II.10 and II.11 can be expressed as

$$G_1 = \left[\frac{1 + \frac{\gamma-1}{F_2}}{1 + \frac{\gamma-1}{F_3}} \right]^{\frac{1}{\gamma-1}}, \quad \text{II.12}$$

$$G_2 = \left[\frac{F_2 + \gamma - 1}{F_3 + \gamma - 1} \right]^{\frac{1}{2}}, \quad \text{II.13}$$

$$G_3 = \left[\frac{F_2 + \gamma - 1}{F_1 + \gamma - 1} \right]^{\frac{1}{2}}. \quad \text{II.14}$$

Equation II.4 can now be written as

$$C_D = \frac{2}{A} \iint_{S_2} G_1 G_2 (1 - G_3) dS_2. \quad \text{II.15}$$

The integrand of this equation is readily evaluated at each grid point in the traverse and the numerical integration technique discussed in Section I.3 of Appendix I can then be used to compute C_D .

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